

A NEUTRON ACTIVATION GAMMA RAY SPECTROMETER FOR PLANETARY SURFACE ANALYSIS

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ABSTRACT

A pulsed DT neutron generator system, similar to that used in commercial well logging, offers the possibility of performing accurate elemental analyses to depths of tens of centimeters in a few seconds with the probe on the body's surface. Through time-phased measurements of the gamma-ray spectrum synchronized with the neutron pulses, concentrations of hydrogen, carbon and key mineral forming elements can be determined even with a low-resolution spectrometer. If a high resolution spectrometer is used, the number of elements measured and the sensitivity for measurement is increased. An implanted probe system, such as in a comet or ice cap penetrator, would offer the highest possible sensitivity.

An inexpensive neutron probe system based on modifications of the Schlumberger well-logging system has been proposed for the Discovery/Venera/SAGE Mission to Venus and the Mars Polar Pathfinder. Preliminary experiments on a simulated Venusian surface indicate that high quality results can be obtained.

INTRODUCTION

There are a number of planned and contemplated NASA, ESA, and Russian solar system lander missions that will characterize planets and small bodies over the next ten years. These include missions to the Moon, Mars, Venus, asteroids and comets. Except for gamma-ray spectrometers, the existing suite of "demonstrated" instruments can only characterize the first fraction of a millimeter of the surface for elemental composition unless drilling or excavating techniques are used. Cosmic-ray induced activation analysis by gamma-ray counting can determine the composition of significant volumes, but only with tens of hours counting time for high quality measurements.

The new era of lower cost solar system exploration missions introduces constraints on the options for the science instrument systems. The selected science payload must always meet the resource constraints of the spacecraft and launch vehicle. The size and capabilities of the spacecraft and launch vehicle will most **often** be selected for their cost. It is also necessary to select the set of instruments that provides the optimum science return within the overall cost and resource constraints. This can mean only a few instruments are flown if expensive innovation is needed in the essential payload, or quality of science return maybe sacrificed if existing instrument designs are used. However in some cases there are options for innovative instruments, use of existing designs for some instruments and space **craft**, and low cost implementation modes that can produce an exceptionally high value science return, This is the case with the proposed Discovery **Venera** Surface Atmospheric Geochemistry Experiment (SAGE) Mission.

The SAGE mission proposes that a select set of U, S. and Russian built instruments be flown on a Russian built Venus lander of the Vega design with a Russian provided launch vehicle. The proposed instrument set includes a new atmospheric chemical analyzer for descent operation, a surface imaging spectrometer for mineralogical identification, an Alpha Proton X-ray analyzer for elemental analysis of a retrieved sample, and the new Neutron Activation Gamma-Ray Spectrometer (NAGS) for analysis of the Venusian surface in-situ.] The APX and NAGS elemental analyzer systems are complementary. The APX system provides elemental analysis of a surface sample obtained by an external drilling system identical to that used on the **Venera** 13, 14 and Vega 1, 2 **landers**.² The drilling system can retrieve a sample of 1 to 6 cm³ from the top few centimeters of the **surface**. The NAGS system on the other hand can provide an **analysis** of hundreds of cm³ of the **surface** without the necessity for retrieving it. Thus a comparison of results can provide an indication of changes in chemistry in the first few centimeters depth due to atmospheric interaction. The APX experiment will determine the abundance of elements from C through Ni with concentrations greater than 1 to _{50/0} by weight, The NAGS system will measure the abundances of H, C, O, Na, Al, Si, S, Ca, Ti, Fe, **Gd+Sm**, plus Cl and Mg (if present in appreciable quantities) by means of neutron inelastic scattering, capture, and delayed radioactivity. The sensitivity will be better than 0.1 % in most cases, with **Gd+Sm** measured at ppm levels, In addition the natural **radioactivities** of K, Th and U will be measured at the site. The thick Venusian atmosphere prevents significant cosmic ray induced gamma-ray activation.

INSTRUMENT SYSTEM

The NAGS instrument is based on the hardware and analytical principles developed by **Schlumberger**, Inc. for petroleum well logging. The instrumentation consists of a small deuterium-tritium neutron generator (DT minitron), its 80 kV high voltage power supply, a scintillator with a miniature, rugged ceramic **photomultiplier** tube and amplifier, and control electronics. **Schlumberger** has developed a number of configurations, but the most suitable one houses all components in lengths of 5.7 cm diameter cylinders that are interconnected and stacked for lowering into a bore hole. The commercial systems are engineered for continuous operation in very harsh down-hole conditions, up to 200° C, hundreds of Gs transient accelerations, and 20,000 lb/in² pressures (with steel housing), These basic components can readily be adapted to a number of planetary applications.

For the **Venera/SAGE** mission, the commercial system, with minor modifications, would be reconfigured and additionally packaged for the Venus surface environment so that it can be deployed from the lander. The instrument will be deployed to a distance of one to two meters by means of an arm that folds out from the side of the lander. The control and data acquisition electronics are divided between the deployed system and the lander. Measurements could be made with the NAGS system fixed at the bottom of the lander, however that position makes it particularly vulnerable to damage on landing, and it maximizes the neutron interaction with the lander, and thus decreases the sensitivity for the **geochemical** measurements. Deployment to one or two meters **will** decrease the gamma-ray signal from the spacecraft itself by one or two orders of magnitude.

The harsh Venusian environment, approximately 500 C and 100 atmospheres pressure at the surface, requires extraordinary thermal and mechanical designs for the lander and externally deployed instruments. Despite the inclusion of extensive thermal insulation and heat absorbers, the **Venera** and Vega landers are limited to, at most, two hours of surface operations. Preliminary analyses indicate that the NAGS system can be made to last two hours using the packaging system illustrated in Figure 1. The primary insulation is a metal vacuum **dewar** that completely

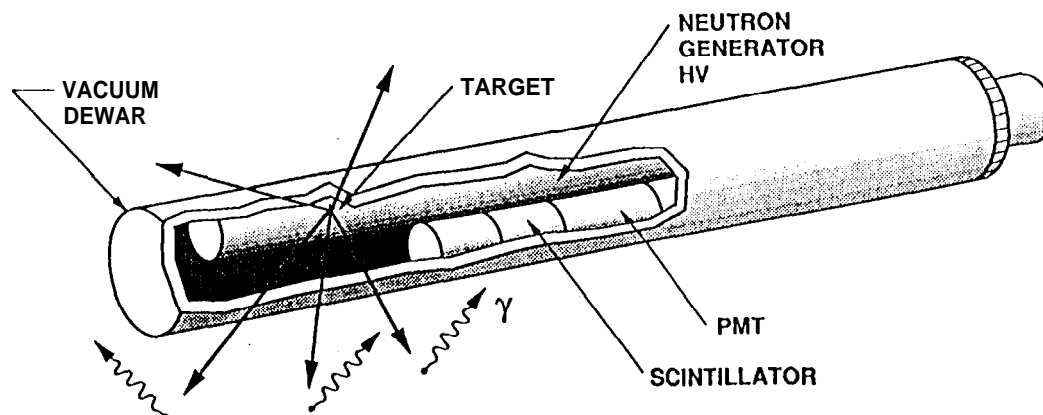


Figure 1, Schematic of packaging system for the NAGS in Venus environment

contains the neutron generator, spectrometer and electronics. Overall the **dewar** is about 1 meter long and 15 cm in outside diameter, 11 cm inside diameter. The vacuum wall contains high temperature **multilayer** insulation. The power and signal lines are carried through insulated connectors at one end. In order to limit the temperature rise rate, the voids within the inner **dewar** wall are filled with a heat absorbing phase-change material. Because the logging systems are mechanically and electrically designed for harsh deep-well conditions, no significant re-engineering of the generator and spectrometer systems is anticipated. The complete system would have a mass of about 27 kg including the thermal packaging. Approximately 30 W would be consumed to maximize neutron output for the operating period. This mass and power is well within the capability of a Vega lander to deliver and operate. For a less severe planetary environment, such as Mars, the neutron probe system mass and power requirement **would** be less by, perhaps, an order of magnitude.

In well logging applications the neutron generator and gamma spectrometer systems are in one linear string with neutron scattering material between them to minimize line-of-sight neutron interaction. However a completely in-line system would be too long to be accommodated on a **Venera/Vega** lander. Thus the neutron generator with its power supply are placed beside the spectrometer system with the scattering material close to the **scintillator**. This is still excellent geometry.

Clearly there are important similarities and differences between using the NAGS system in a petroleum **well** and on the surface of a planet, Venus in particular. In both cases, the system must be mechanically and electrically rugged. In both cases the system must produce high quality spectral data under extreme mechanical stress and rapid temperature changes. The ability to perform well under these conditions is **fundamental** to the existing commercial logging systems.

The two most important differences between well logging and the **planetary** system are the **geometry** and the amounts of neutron moderator present. In a well logging application, the neutrons are interacting with rock that is nominally in 4π geometry around the source and detector, whereas in the case of the surface location, the material to be analyzed is only in one hemisphere. This has the effect of decreasing the overall sensitivity of measurements because approximately half the neutrons will never interact with the solid surface, and additional neutrons will be scattered out of the solid before they are captured.

The second major difference **from** well logging is the relative amounts of neutron moderator present. In well-logging applications the generator is always surrounded by significant concentrations of hydrogen-containing fluids such as water and hydrocarbons. These act to very efficiently slow down the neutrons so that they are captured within a few tens of centimeters from the generator. Thus the gamma ray signal from neutron capture is strong in a **scintillator** close to the generator. On the other hand, on Venus or other “dry” planets there is little or no hydrogen present so that the neutrons may travel several times farther before they are captured. Thus the optimum capture signal may be obtained farther from the generator.

Data Acquisition

The data acquisition strategy has been **well** developed for the well logging applications, and an essentially similar strategy is used for a planetary **application**.³ The gamma-ray signal at the spectrometer detector contains components from neutron inelastic scattering, neutron capture, and delayed radioactive decay. The separation of these components can enhance the sensitivity for some elements. Although the gamma ray spectrum from each element is unique, when the spectrum is derived from a relatively low resolution detector, such as the **scintillator** system, the lines are not uniquely resolved and separation of components is a considerable advantage. Thus the strategy is to measure the gamma rays as a function of time following a microsecond burst of neutrons. The inelastic scattering of the primary 14 MeV neutrons, (n,n') reactions, results in immediate emission of gammas from the excited nuclei. The capture of the neutrons by target nuclei, (n,γ) reactions, results in prompt emission of gamma rays, but there is a delay of some microseconds between emission of the primary neutrons and the capture because capture is more

likely for slow neutrons. The emission of gammas by decay of activated nuclei is statistically delayed by the half life of the nucleus.

A typical data acquisition scenario is as follows. The neutron generator is pulsed on for about 10 microseconds every millisecond. A "pulse gate" gamma spectrum is accumulated during the pulse. This spectrum is dominated by (n,n') reactions. Then a "capture" spectrum is accumulated for a few hundred microseconds. This spectrum is dominated by the (n, γ) reactions. Then, perhaps with some hundreds of microsecond delay, the "delay activation" spectrum is accumulated for a few hundred microseconds. This spectrum is dominated by decay of radioactive nuclei. The **intercomparison** of these spectra, and subtraction of various components allows analysis for H, C, O, Na, Al, Si, S, Ca, Ti, Fe, Gd+Sm, plus Cl and Mg (if present in appreciable quantities) with sensitivities of better than 0.10% for most components and Gd+Sm with ppm sensitivities. The **quantitation** process has been described elsewhere.^{4,5}

EXPERIMENTAL TESTS

A number of laboratory experiments were performed to investigate the quality of the spectra that could be obtained on the Venusian surface by a neutron generator (output $> 10^8$ n/sec) with a 3.5 cm diameter x 7.5 cm **cerium-doped gadolinium oxyorthosilicate (GSO)** gamma-ray detector. Simulations of the Venusian surface were made in a 68 cm x 99 cm x 75 cm polyethylene container. Initial measurements were made with a **CaCO₃-filled or SiO₂-filled** container. These measurements were intended to evaluate the effects of the CO₂ atmosphere on the shape of the spectra and to "salt" the formation with individual elemental compounds to evaluate the spectral shapes for each individual element. Subsequently, a simulation of the Venusian surface was constructed to provide a close approximation of the elemental content from the results obtained by Venera 14.6 The elemental content of the resultant simulation is compared with the Venera 14 results in Table 1.

All measurements were performed with the neutron generator, shielding, and the **detector-photomultiplier** combination lying on the surface of the formation, as shown schematically in Figure 2. Since the Venusian environment is characterized by being essentially hydrogen free, the

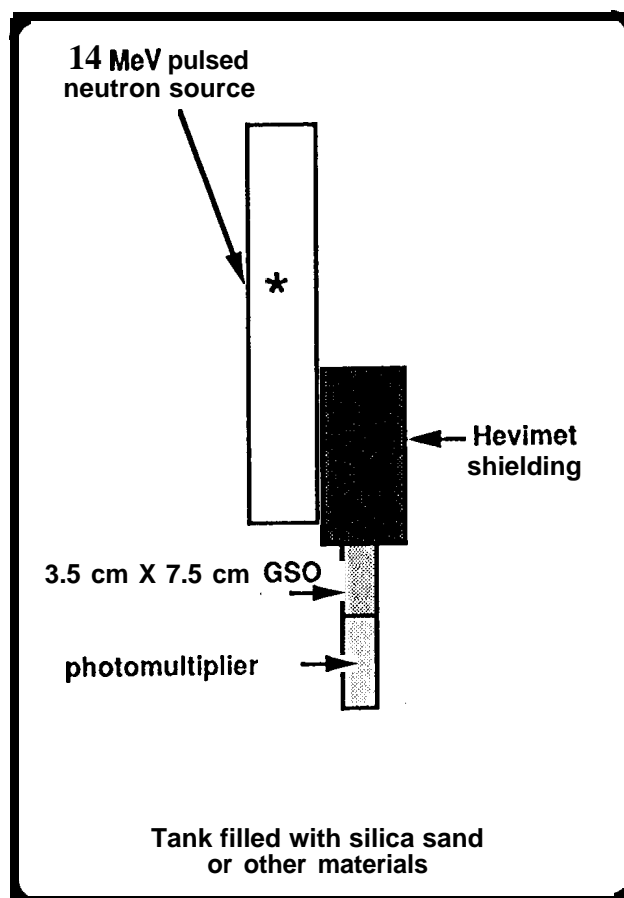


Figure 2. Schematic drawing of the top view of the laboratory experimental setup.

slowing down and **diffusion** properties of neutrons are controlled by the other light elements present, rather than hydrogen as is usually the case on Earth, As there is uncertainty on how much of the CO₂ atmosphere may permeate the Venusian soil and on whether there will be a portion of the atmosphere between the neutron generator and the detector and the soil being measured, we attempted to evaluate the effect of the variation of neutron moderation properties on detected gamma-ray spectral shapes by comparing simple spectra obtained with and without substantial CO₂ present. Spectra were obtained by placing the neutron generator and detector directly on the SiO₂ soil surface and by repeating the measurement with a 5 cm layer of solid CO₂ between the neutron generator and detector and the soil surface.

To provide an estimate of the spectral shape for individual elements, packages, containing typically 1 kg of individual element oxides or carbonates, were placed about 10 cm beneath the CaCO₃ soil surface between the neutron generator and the GSO detector. The resulting spectra will provide individual spectral response **functions** after subtracting the contribution from the common CaCO₃ content.

Table 1. Comparison between elemental content determined by Venera 14 and the laboratory Venusian simulant.

Element	Venera 14 Measurements (wt percent)	Venusian Simulant (wt percent)
Magnesium	4.9	4.3
Aluminum	9.5	7.9
Silicon	22.7	19.5
Potassium	0.17	0.65
Calcium	7.4	7.2
Titanium	0.75	0.75
Manganese		
Iron	6.8	6.8
Sulfur	0.35	0.27
Chlorine	0.4	0.42
Oxygen	43.6	47.5
Carbon		4.3
Sodium		0.28
Unknown	3.3	

All electronics for processing the detector outputs used standard laboratory electronics. Spectra to reflect the fast neutron-induced gamma rays, those due to thermal neutron capture reactions, as well as the spectrum of gamma rays from the decay of delayed radioactivity were obtained by gating the detector electronics with signals from the pulse from the neutron generator.

RESULTS

The test of the effect of the CO₂ atmosphere can be seen in the capture spectra shown in Figure 3. If there were significant changes introduced by the CO₂ atmosphere, then a change in

the peak height to scattered background would be expected. The figure shows the gross thermal neutron capture gamma-ray spectrum without any CO₂ present (dashed curve) with the corresponding spectrum obtained with the 5 cm of CO₂ between the equipment and the formation surface (solid curve). The only significant change in the spectral shape is from the additional oxygen activation photopeaks (the triplet at roughly 6, 5.5 and 5 MeV) and the Compton background to lower energies from these peaks. In the region of the silicon thermal neutron capture gamma-rays, there is no significant change in the peak or background portion of the spectrum when the solid CO₂ is introduced. Thus the shape of the gamma-ray standards are expected to be minimally perturbed by the exact amount of CO₂ atmosphere present during the measurement, indicating that this factor would probably not be an important limit on the accuracy of derived elemental concentrations.

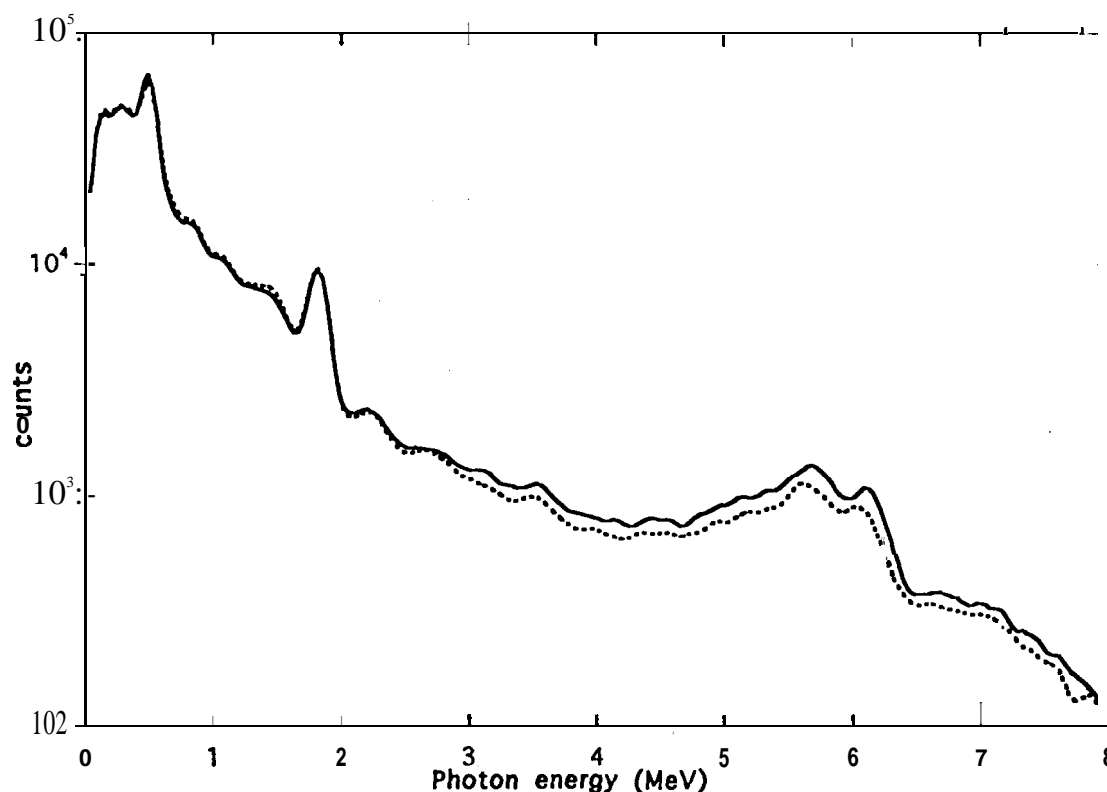


Figure 3. Comparison between thermal neutron capture gamma-ray spectra obtained on a quartz formation with (solid curve) and without (dashed curve) CO₂ between the surface and the instrument.

Two typical neutron capture gamma-ray spectra are shown in Figures 4 and 5 where TiO₂ and Fe₂O₃ are salted in the CaCO₃ matrix. In both cases the contributions from the added elements can be clearly identified. These spectra confirm that elemental standards could be derived for the response of the spectrometer to individual elements contained in the measurement volume.

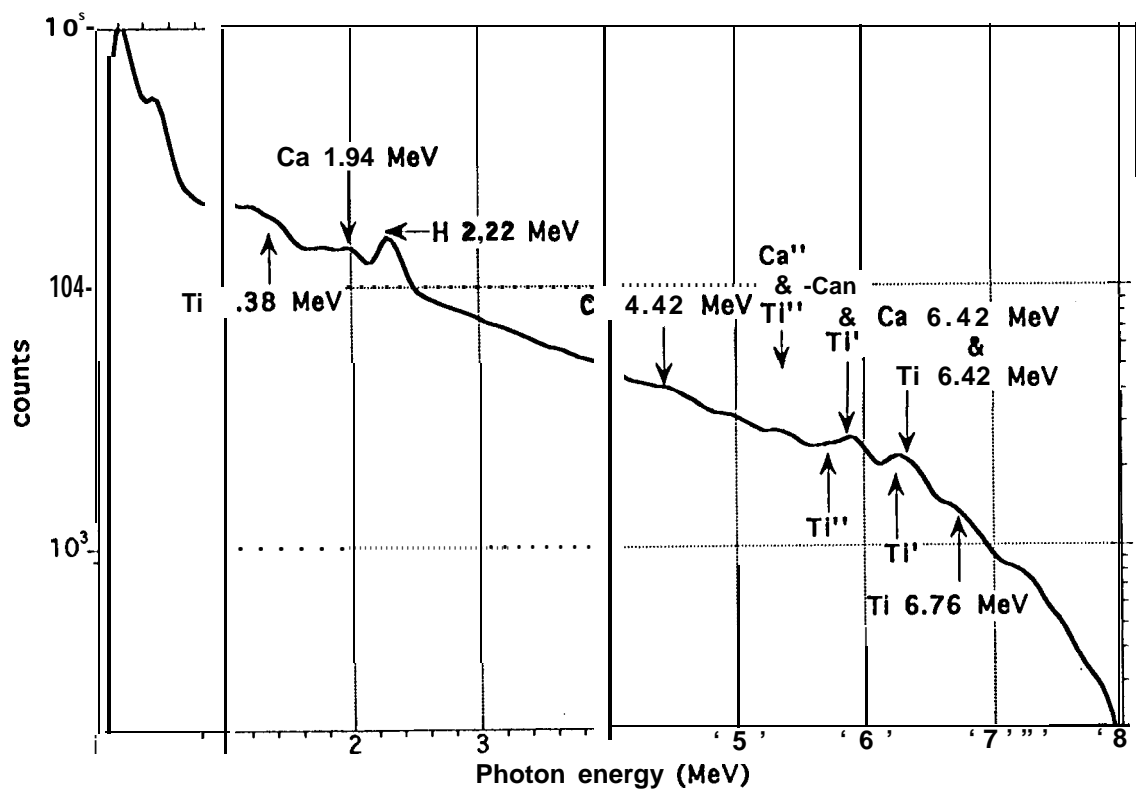


Figure 4. Thermal neutron capture gamma-ray spectrum when the calcite simulation is "salted" with TiO₂.

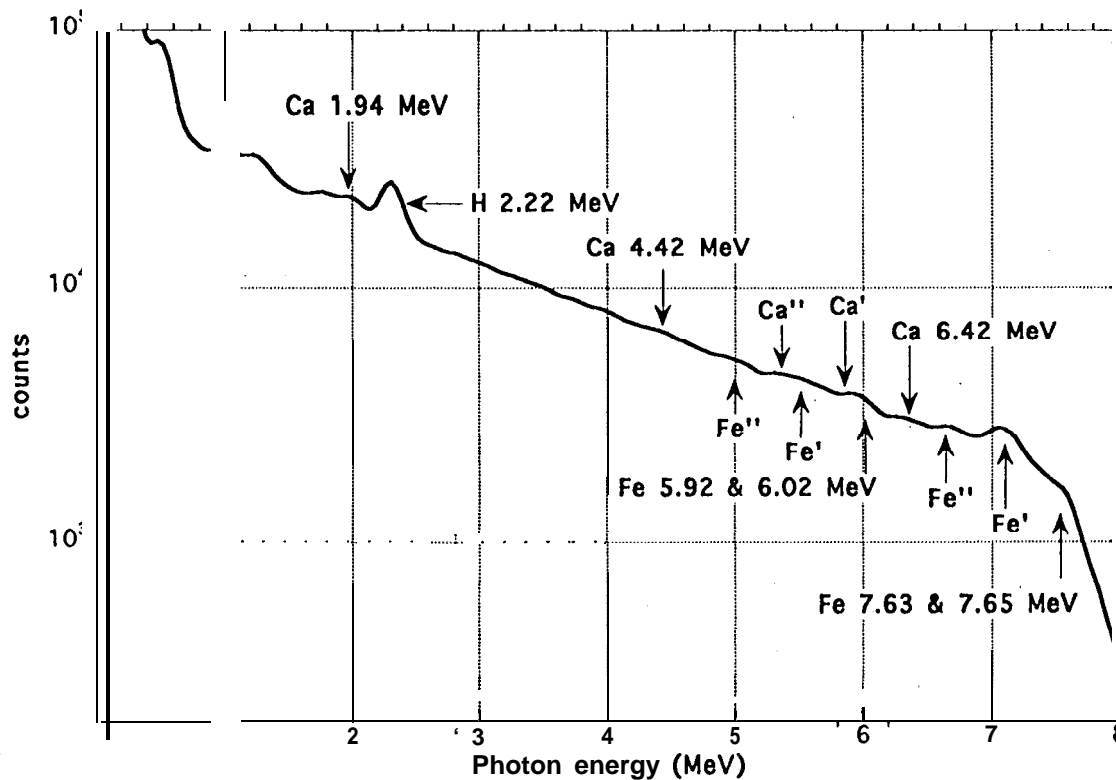


Figure 5. Thermal neutron capture gamma-ray spectrum when the calcite simulation is "salted" with Fe₂O₃.

Figure 6 shows a thermal neutron gamma-ray capture spectrum obtained with boron surrounding the detector to minimize the spectral contribution **from** the detector package. This spectrum was obtained in the complete simulation, whose elemental content is shown in Table 1. Numerous peaks can be identified from the elements in the simulation, indicating that these elements, as well as perhaps some of the others whose peaks are not visually obvious, **can** be quantitatively determined. It should be noted, of course, that some of the elements would be determined from prompt neutron-induced reactions, such as carbon, oxygen, and magnesium, and from delayed radioactivity, such as aluminum, manganese, and sodium,

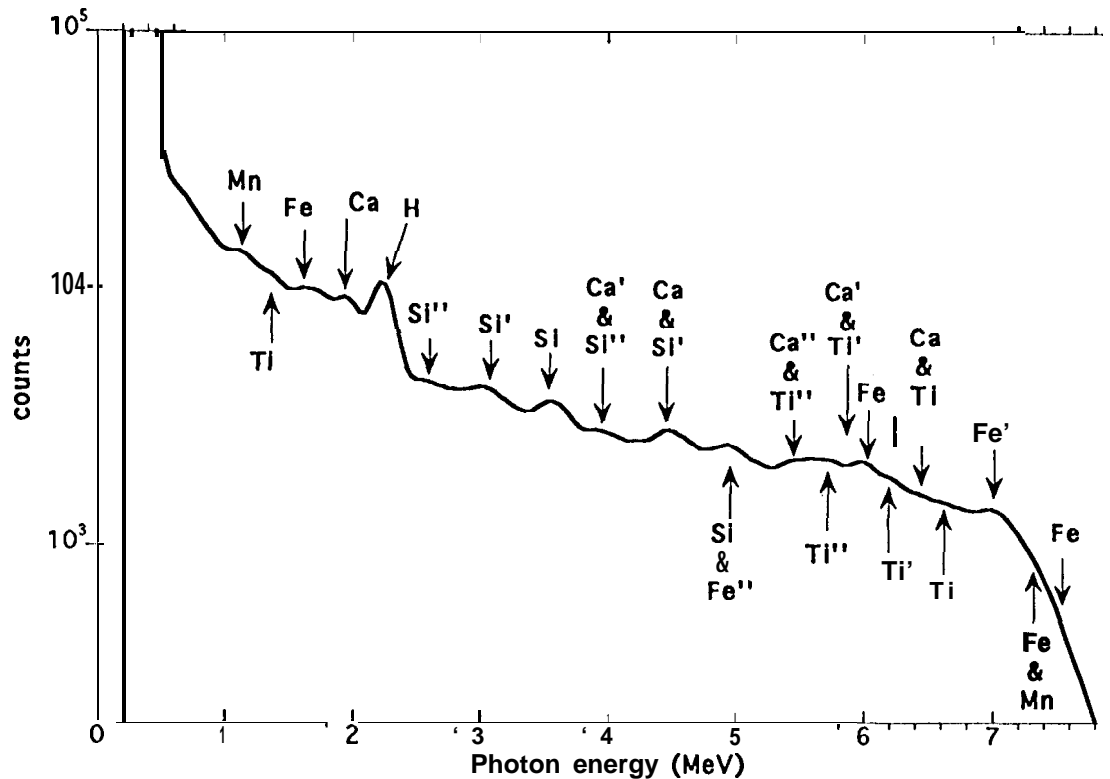


Figure 6. Thermal neutron capture gamma-ray spectrum in the complete simulant model whose composition is given in Table 1. The hydrogen peak is from the environment surrounding the simulant.

DISCUSSION

The technique of using a gamma-ray detector together with a pulsed neutron generator to determine accurate elemental abundances has been well developed for remote sensing applications on Earth in rugged environments. Such systems can be applied to non-orbital planetary environments to provide elemental concentrations of the surface constituents averaged over the first tens of centimeters in depth. In an impact scenario a volume of tens of centimeters in radius around the probe location can be analyzed. The particular choice of system components for planetary missions is governed by the particular mission environment. The selection of GSO for the Venusian measurement is based on its properties at elevated temperatures where it can maintain a good light output with an acceptably fast scintillation light decay constant over the

entire range of anticipated measurement temperatures. In addition, it provides a good volumetric detection efficiency, minimizing the size of the dewar while maintaining a good gamma-ray spectral response. For a colder environment, a better choice might be **cerium-doped lutetium oxyorthosilicate**⁸ which has a faster decay time, essentially the same volumetric detection efficiency as BOO and has essentially constant output and time characteristics between 11 K and room temperature, providing better spectral stability and easier electronics design. Of course, in situations where no neutron generator is provided (i.e., using cosmic rays to induce the reaction gamma rays) other detectors such as BOO maybe more than adequate. When extensive **multielement** analysis is required, a neutron generator can be coupled with a germanium detector for optimum energy resolution and detection sensitivity.

The data presented here are not sufficient for making accurate predictions of anticipated statistical uncertainties or minimum detection limits for the **Venera** measurement. However, experience has indicated that when even a hint of spectral peaks can be seen in the measured spectrum acceptable precision can be obtained for the elements that make a reasonable spectral contribution to the measurement. In fact, it is possible to **quantify** elemental concentrations at reasonable levels of precision even when there is no visual indication of specific peaks. Laboratory measurements can be used to predict quantitatively the **performance** of such a system under a particular planetary measurement environment⁹, but resources were not available to perform the complete study here,

These measurements do **confirm**, however, that the use of a gamma-ray detector with pulsed neutron generator in the Venusian environment can **perform** a significant elemental analysis to provide greater insight into the nature of the surface rocks on the planet. The application of this technique to planetary environments with significantly different surface constituents, such as comets, is currently being evaluated.

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